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FINAL TECHNICAL REPORT

Project A-3172

VLF HAZARDS ANALYSIS

July 1982

BY

D. J. Schaefer, W. B. Warren, and F. L. Cain

Submitted Under

Subcontract No. SCEEE ARB/82-65

to

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FOREWORD

The hazard analysis for the 10 kHz to 3 MHz frequency range described in this report was conducted in the Biomedical Research Division of the Electronics and Computer Systems Laboratory in Georgia Tech's Engineering Experiment Station. This work was sponsored by the U. S. Air Force School of Aerospace Medicine under Contract No. F33615-78-D-0617 with the Southeastern Center for Electrical Engineering Education, Incorporated (SCEEE). The SCEEE then subcontracted the hazard analysis study to Georgia Tech under Subcontract No. SCEEE ARB/82-65. The period of technical performance was 5 February 1982 through 1 June 1982. Mr. Stewart Allen of the Air Force School of Aerospace Medicine served as Program Manager.

The goals of this research were to survey existing literature to ascertain what known hazards exist in the 10 kHz to 3 MHz frequency range, to analyze the hazard problem to determine what parameters should be monitored and what types of hazard are likely to occur, to recommend a tentative safety standard, and to identify problem areas that require further investigation. Approximate mathematical models were developed to permit estimates of whole body Specific Absorption Rate (SAR) values, localized SAR values, whole body current, and localized and whole body current densities. Recommendations for a tentative safety standard and identification of problem areas were made.

Respectfully submitted,

—
Fred L. Cain
Principal Investigator

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I. INTRODUCTION

Along with the growing public awareness of environmental issues in recent years, questions have arisen concerning the safety of non-ionizing electromagnetic radiation. These questions have led to research to investigate what physical parameters perturb the biology of an organism and to determine what the power absorption characteristics of organisms are as a function of frequency. In addition, safety standards have been formulated for frequencies ranging from 300 kHz to 300 GHz [1]. The purpose of the present study is to identify what considerations should go into the formulation of a safety standard in the 10 kHz to 3 MHz frequency range and to propose a tentative safety standard.

For a safety standard to be of practical value, it must be based on easily measured parameters. Values of body current, current density, specific absorption rate (SAR), and other such quantities which are internal to the body may not be readily detectable. Thus, it was decided that the standard should be based upon electric field strength and magnetic field strength and the size of metallic objects (in the case of contact hazards). Approximate mathematical models were developed to relate SAR and induced currents to the field strengths. The electric and magnetic field vectors are treated independently since regions of high exposure levels are likely to occur in areas other than those where uniform plane waves propagate. In such regions, the majority of the available energy may predominantly be in either the electric or magnetic field. Consequently, the model permits calculation of SAR and currents from the electric and magnetic field components separately.

Using the methods discussed above, the following work on VLF Hazards Analysis was accomplished on this project:

- Proposal of a tentative safety standard for the frequency range of 10 kHz to 3 MHz,
- evaluation of the 100 mW/cm^2 incident power level as a safety standard in the 10 kHz to 3 MHz frequency range,
- identification of problem areas in determining a safety standard,
- evaluation of shock and burn hazards as functions of body current and/or current density and frequency,
- evaluation of burn and shock hazards from common metal objects (automobiles, guy wires, etc.),

- development of approximate equations which can be used to find induced currents and specific absorption rates under "worst case" conditions independently for both the electric and magnetic field vectors,
- calculation of localized heating based on the approximate model for various regions of the body, and the
- calculation of localized current densities for various regions of the body.

The analyses presented in this report are valid for continuous wave (CW) exposures. The results for pulse modulated exposures can be derived from the CW predictions for pulse periods which are relatively short (less than a few seconds). The CW SAR values multiplied by the duty factor (pulse duration divided by the pulse period) yield the SAR values for pulsed modulation. Similarly, average values for the induced currents may be found by multiplying the CW values by the duty factor of the pulsed radiation. Peak values of the current must be used in SAR calculations (as they are in the methods described above) and in predicting shock threshold levels. Thresholds for burn hazards from pulsed current should be proportional to the peak current times the square root of the duty factor.

Subsequent sections of this report deal with the literature search, details of the analysis, assumptions, tabular data, identification of problem areas, and conclusions concerning needed future work. A tentative standard is suggested.

II. RESULTS OF LITERATURE SEARCH

A literature search was conducted to determine what is currently known about bioeffects, hazards, and dosimetry in the 10 kHz to 3 MHz frequency range. In addition, information in other frequency ranges was gathered in the hope that it would shed some light on similar phenomena at frequencies relevant to this study. Some of this information included effects of high field strengths, since it was anticipated that this information would be useful.

As anticipated, little information was found on bioeffects at frequencies of interest to this study. However, studies, concerned with a number of potentially important parameters (mostly at frequencies outside the range of this report), were found and are discussed in this section under the appropriate headings.

A. SAR Literature Values

A good deal of theoretical work on whole body SAR over a wide range of frequencies has been reported [2,3,4,5,6]. These values were obtained by modeling the human body as some relatively simple geometrical object and in many cases assuming the body to be composed of a homogeneous material whose complex permittivity is 0.67 times that of muscle for a given frequency. Various numerical methods are then employed to obtain the whole body SAR.

The maximum SAR for a fixed incident power density occurs at approximately 70 MHz for a man standing erect with the electric field vector aligned with the long dimension of the man [3]. In experimental animals, it was determined that the highest safe whole-body SAR level is 4 W/kg [1]. For safety this factor was reduced by a factor of ten (to 0.4 W/kg) in formulating existing safety standards [1].

In Table 1, literature values [2] are listed for the whole body SAR which results from exposure to plane wave with a 1 mW/cm^2 incident power density. These values will be used in another section of this report to calculate maximum allowable power densities and electric field strengths assuming whole body SAR is the only parameter to be considered. Also listed in Table 1 are values for the relative dielectric constant, ϵ_r , and conductivity of the body, σ , as a function of frequency. These values are 0.67 times literature values for muscle [3].

TABLE 1
SAR LITERATURE VALUES FOR A PLANE WAVE
WITH A 1 mW/cm^2 INCIDENT POWER DENSITY

(kHz) FREQUENCY	(W/kg) SAR	(ohm ⁻¹ m ⁻¹) $\sigma_{\text{BODY}} = .67 \sigma_{\text{MUSCLE}}$	$\epsilon_{\text{BODY}} = .67 \epsilon_{\text{MUSCLE}}$
10	5.0×10^{-9}	0.214	3.3×10^4
100	3.0×10^{-7}	0.329	1.7×10^4
1000	2.7×10^{-5}	0.367	1.3×10^3
3000	2.0×10^{-4}	0.383	9.4×10^2

B. Literature on Hazards Due to Current

Little information was found in the literature concerning what levels of body current or current density are harmful in the 10 kHz to 3 MHz frequency range. Current flowing through a living organism can have three general effects [7]: (1) it can cause resistive heating of the tissue, (2) it may cause electrical stimulation of excitable tissue, and (3) it may cause electrochemical burns in the case of direct current. While the severity of all these effects must ultimately depend upon current density, most of the work reported in the literature is in terms of body current. Kleronomos and Cantwell [8] and Dalziel [9] report that at 60 Hz a body current of 18-30 mA may cause respiratory arrest. In this phenomenon, the respiratory muscles contract severely enough to result in asphyxiation unless the current flow is stopped. At 60 Hz, current levels of 75 to 400 mA result in ventricular fibrillation [7,8]. This may continue even in the absence of the current and result in death. At currents from 1 to 6 A, myocardial contractions occur at 60 Hz [7,8]. Doses below 1 A/kg cause no irreversible damage, but above this level damage may occur [7,8,10,11]. Tissue burns begin at current levels above 1 A for 60 Hz current and may be especially a problem above 5 A [7,8]. The temperature elevation of the skin in direct contact with an electrode is a function of the current density, conductivity, the area of contact, and the length of time of the contact [8,12]. High current levels cause the brain and nervous tissue to lose all functional excitability [7].

Burns caused by high currents from electrosurgery devices which operate from 500 kHz to 2 MHz have been studied and are relevant [13,14]. Becker [14] found that current densities of 100 mA/cm^2 (or 1000 A/m^2) for ten seconds cause skin damage. The skin temperature is directly proportional to the time and the square of the current density [12]. Thus, as the exposure time is increased, the current required to produce damage is reduced by the square root of the time factor. A six minute exposure may result in skin damage at a current density of 166.67 A/m^2 provided the equations hold true for these conditions.

Studies [1,9] have been conducted on the biological effects of current as a function of frequency. Studies of the let-go currents in the 2-20 MHz band indicate that 200-500 mA is the upper safe limit of current [1]. At 100 kHz this value falls to 150 mA [1] while at 10 kHz it falls to 95 mA (extrapolated from [9]). These values were used to evaluate the hazards from VLF current flow in subsequent sections of this report.

C. Literature on High Electric Field Effects

Later in this report, it will be shown that if whole-body SAR is used as the sole criterion for setting a safety standard, high field strengths would be permitted. For this reason, a literature search of the effects of high field strengths was conducted. Voltages above 240 volts on electrodes in direct contact with the skin at 60 Hz may puncture the skin [7]. Electric field strengths on the order of 10 kV/cm (10^6 V/m) cause partial strand separation of DNA molecules [15]. Electric field strengths of 30 kV/cm (3×10^6 V/m) induce pores in biological membranes [16]. Electric fields of 205 V/cm (20,500 V/m) at 20 MHz have been used to kill bacteria and fields as low as 22 V/cm (2,200 V/m) have been used to kill tissue culture cells [17] without raising the temperature. Friend found that the morphology of amoebas can be changed as a function of frequency and electric field strength with cellular destruction occurring at 100 kHz in an electric field of 200 V/cm (20,000 V/m) [18]. Teissie was able to fuse cells in tissue culture with electric field strengths of 2 kV/cm (200,000 V/m) [19].

High electric field gradients can generate forces on cells [20]. Pohl has been able to use these forces to separate living and dead yeast cells; to distinguish among normal, male hemophilic, female hemophilic, and female transmitter canine thrombocytes; and to distinguish between yeast cells grown on different culture media using electric field strengths typically of 100 V/cm (10,000 V/m) [21,22]. Recently, Haber discovered that he could make non-polar molecules migrate at very high velocities in electric fields with field strengths of 500-2000 V/cm (50,000 - 200,000 V/m) [23].

D. Miscellaneous Literature Findings

Some other useful information was found in the literature. Cook published a study on the pain threshold for 3 GHz radiation. He found that approximately $1,000 \text{ mW/cm}^2$ was the pain threshold for direct contact with an open-ended waveguide [24]. Bridges and Preache reviewed the bioeffects literature for effects at 60 Hz [25]. Their conclusion is that no bioeffects have been conclusively demonstrated to date. Tucker and Schmitt tested human perception of magnetic fields of moderate strength (7.5 - 15 gauss) at 60 Hz [26]. In over 30,000 trials they found no significantly perceptive individuals. Fleming compared the effects of high current versus high electric field gradients on bacteria viability using a frequency of 333 MHz [27]. He found that the high field gradients were more effective at killing the bacteria by more than two orders of magnitude than the high currents. This work was not well

documented, but it does show that caution should be exercised in permitting exposures to very high electric fields.

III. ALLOWABLE FIELDS FOR AN SAR OF 0.4 W/kg

As mentioned previously, literature values of SAR as a function of frequency for plane wave with a given power density are available [2,3,4]. In addition, it is known [1] that a whole-body SAR value of 0.4 W/kg is considered to be safe and has been used in determining safety levels for exposure in other frequency ranges. Clearly, the first task of the present study had to be to estimate what power densities and field strengths would be permitted for a value of 0.4 W/kg for the SAR, assuming that the SAR predictions found in the Radiofrequency Radiation Dosimetry Handbooks [2,3,4] are correct and that no other criteria enter into the formulation of a standard. This task can be done since the SAR increases directly with increases in the power density of the incident field. Given the incident power density and given that a plane wave exists, the electric field strength, E (in V/m), the magnetic field strength, H (in A/m), and the power density, P (in mW/cm²), are related as follows (for propagation in air):

$$E = 61.4 \sqrt{P}, \text{ and} \quad (1)$$

$$H = 0.163 \sqrt{P}. \quad (2)$$

The power density for the plane waves listed in Reference [2] is 1 mW/cm². The power density (in mW/cm²) required to produce a whole-body SAR value of 0.4 W/kg is related to the SAR value (in W/kg) for a 1 mW/cm² power density, SAR_0 , by the following ratio:

$$P = \frac{0.4}{SAR_0}. \quad (3)$$

Thus, from these equations it is possible to calculate values of the maximum allowable power density, electric field strength, and magnetic field strength for a plane wave propagating in air in order to produce a whole-body SAR of 0.4 W/kg. These results are listed in Table 2.

From the information in Table 2, it is clear that if SAR alone is used as the safety criterion, then very high electric field intensities would be acceptable and fields of 1,000 V/m would be safe at all frequencies. Some of the lower frequency field values are in the range known to affect cells [17-19, 21-23].

TABLE 2
MAXIMUM ALLOWABLE VALUES BASED SOLELY ON A
MAXIMUM SAR OF 0.4 W/kg

FREQUENCY	P_{MAX} (mW/cm ²)	E_{MAX} (V/m)	H_{MAX} (A/m)
10 kHz	8.00×10^7	550,000	1,460
100 kHz	1.33×10^6	70,800	188
1 MHz	1.48×10^4	7,470	19.8
3 MHz	2.00×10^3	2,750	7.29

IV. DEVELOPMENT OF SIMPLIFIED MODEL

The need for a simplified mathematical model capable of predicting whole body SAR, localized SAR, body currents, and current densities was evident. For the purpose of setting a standard for near-field zones, that this model should also be capable of separately finding the SAR due to the electric field and the SAR due to the magnetic field. Since this model is to be used only to provide a rough estimate of the probability of biohazards and to identify areas requiring further research, a very simplified, non-rigorous approach was selected.

It would be possible to predict currents and current densities by using the SAR values found in the literature for plane wave exposures. This approach was not used because no insight is achieved about how various parameters alter the SAR and current densities and because no information about near field SAR and current density values could be obtained in this manner. A very simplified closed-form solution to the dosimetry problem was considered desirable and was undertaken. The development of the model for the electric field SAR and currents and for the magnetic field SAR and currents is discussed below.

A. Electric Field Model

In order to obtain a mathematical model for dosimetry based on the electric field, several simplifying assumptions were made. First it was assumed that the dimensions of the human body are much, much smaller than the wavelength of the radiation (quasi-static approximation). At 3 MHz the wavelength is approximately 100 meters compared to 1.75 meters for the long dimension of a man, so at all frequencies in the 10 kHz to 3 MHz range the quasi-static approximation holds. The quasi-static approximation greatly simplifies the mathematics necessary to find the absorbed power.

To convert the electric field into an absorbed power, it is necessary to find the displacement current and to know the conductivity of the medium, the density of the medium, and the geometry of the object. Boundary conditions dictate that the tangential electric field in the dielectric is equal to the tangential electric field in air while the normal displacement vector is continuous across the air/dielectric interface (see Figure 1). For simplicity, the body initially is modeled as a semi-infinite slab of material with the electric field normal to its surface. The internal electric field for this case is equal to the magnitude of the external electric field divided by the dielectric constant of the medium. If the electric field varies sinusoidally with time,

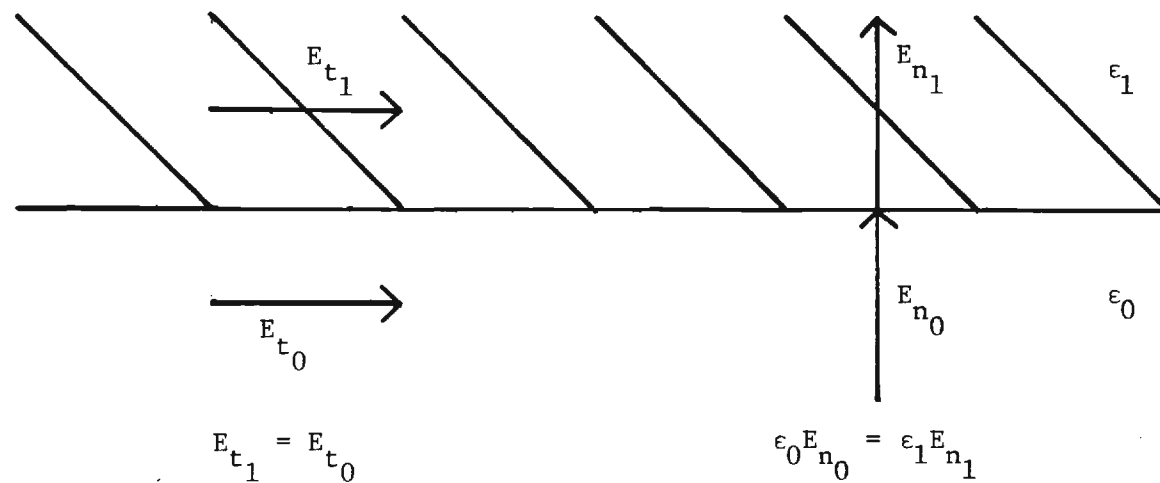


Figure 1. Behavior of the Electric Field at a Dielectric Interface.

then the displacement current density, J_E , is given by [28]:

$$|J_E| = \left| \frac{\delta D}{\delta t} \right| = 2\pi f \epsilon_0 E_0 ,$$

where D is the electric flux density vector, f is the frequency, t is the time, ϵ_0 is the permittivity of a vacuum, and E_0 is the external electric field vector in air.

The Specific Absorption Rate caused by the electric field, SAR_E , is

$$SAR_E = \frac{J_E^2}{2 \rho \sigma} = \frac{2\pi^2 f^2 \epsilon_0^2 E_0^2}{\sigma \rho}$$

where ρ is the density of the body (taken to be 1000 kg/m^3).

The above equation holds at a point, though if average values of the electric field were used, it would be a good approximation for the whole body assuming the boundary conditions are accurate. Due to coupling of the tangential electric field at the front, back, and sides of the body, the internal electric field will be higher than the internal electric field in the center of the body. The tangential electric field (which is the external electric field) will decrease with distance into the dielectric. The rate of the decrease will depend upon the relative dielectric constant of the body at the frequency under consideration. For small relative dielectric constants, the decrease will be slow, while for large relative dielectric constants, the decrease will be rapid. The normal electric field coupled across the tissue/air interface will be high for small relative dielectric constants of the body and vice versa. Thus, for a fixed body and a fixed electric field geometry, the average value of the internal electric field may be expected to be higher than that predicted from normal coupling of the electric field by a factor, K , which to a first approximation, may be independent of the relative dielectric constant. Thus, the equation for current density should be multiplied by the factor K , and the expression for the SAR created by the electric field should be multiplied by K^2 .

In order to arrive at a reasonable estimate for the value of K , calculated values of the whole body SAR from both electric and magnetic field components of a plane wave at 10 kHz were compared with values of SAR in the literature [3]. The values for the magnetic field contributions to the SAR are derived in the next section. From these comparisons, the value of K was found to be 19.33. Inserting the constants in MKS units, the equations become

$$\text{SAR}_E = (2.695 \times 10^{-21}) \left(\frac{f^2 E_o^2}{\sigma} \right) \text{ and}$$

$$J_E = (2.322 \times 10^{-9}) (f E_o).$$

These equations were used in predicting the effects caused by the electric field in the 10 kHz to 3 MHz frequency range. These results are discussed in subsequent sections of this report.

B. Magnetic Field Model

Since the permeability of the body, μ , is essentially the same as the free space value, μ_o , no discontinuity of the magnetic field vector occurs at the air/body interface. Maximum currents will be induced into the body when the magnetic field vector is normal to the body surface having the maximum area (the front or back of the body). The current density induced by the magnetic field is found starting with the following equation:

$$\oint \vec{E} \cdot d\vec{l} = - \mu_o \int_s \frac{\delta \vec{H}}{\delta t} \cdot d\vec{S} \quad ,$$

where $d\vec{l}$ is the infinitesimal length element and $d\vec{S}$ is the infinitesimal surface element.

If one assumes that the magnetic field varies sinusoidally, the magnetic field vector may be expressed as

$$\vec{H} = H e^{j\omega t} \hat{S} \quad ,$$

where H is the maximum value of the magnetic field intensity and \hat{S} is a unit vector normal to the surface of the body (assuming maximum coupling of the magnetic field to the body). The induced electric field vector will be normal to the magnetic field and will have circular symmetry. Since the maximum value of the current induced by the magnetic field occurs on the circular boundary, a worst case condition can be obtained by assuming this maximum value exists uniformly over the entire circular area, and also assuming that the electric field vector is parallel to the length element while the magnetic field vector is parallel to the surface element. Thus, one has

$$|2\pi a E_\phi| = \omega \mu_o H \pi a^2 \quad , \text{ and}$$

the current density, J_H , is

$$J_H = \sigma |E_\phi| = \sigma \mu_o H \pi f a \quad .$$

The body from the front (or back) may be modeled (Figure 2) as a rectangle in which three circles of radius 0.254 meters may be drawn to approximate the area. The worst case current density will occur for this maximum radius. This value may then be used to calculate the specific absorption rate due to the magnetic field, SAR_H :

$$SAR_H = \frac{J_H^2}{2\sigma\rho} = \frac{\sigma f^2 \mu_o^2 H^2 \pi^2 a^2}{2\rho}$$

Upon inserting the values of the constants in terms of MKS units, the magnetic field equations reduce to

$$SAR_H = (5.0276 \times 10^{-16})(\sigma H^2 f^2) \quad \text{and}$$

$$J_H = (1.003 \times 10^{-6})(\sigma f H).$$

The hazards caused by the magnetic field were analyzed using these equations. The results are discussed in the sections to follow.

C. Comparison of Model Predictions to Literature Values

Comparison with literature values was undertaken to establish the accuracy of the model. In Table 3, comparisons of predicted values to values found in Reference [3] are made. From this table, it is evident that the model does predict values that are close to those values reported in the literature for exposure to 1 mW/cm² plane wave. However, it should be noted that since the model derived in this report does not require the exposure field to be a plane wave, it may be useful in predicting hazards under more realistic conditions, such as exposure in the induction field of an antenna.

Tell [29] has derived an equation to predict the contributions to whole-body SAR from the magnetic and electric fields separately at 10 kHz:

$$SAR = 3.0 \times 10^{-12} E^2 + 1.2 \times 10^{-8} H^2 \quad .$$

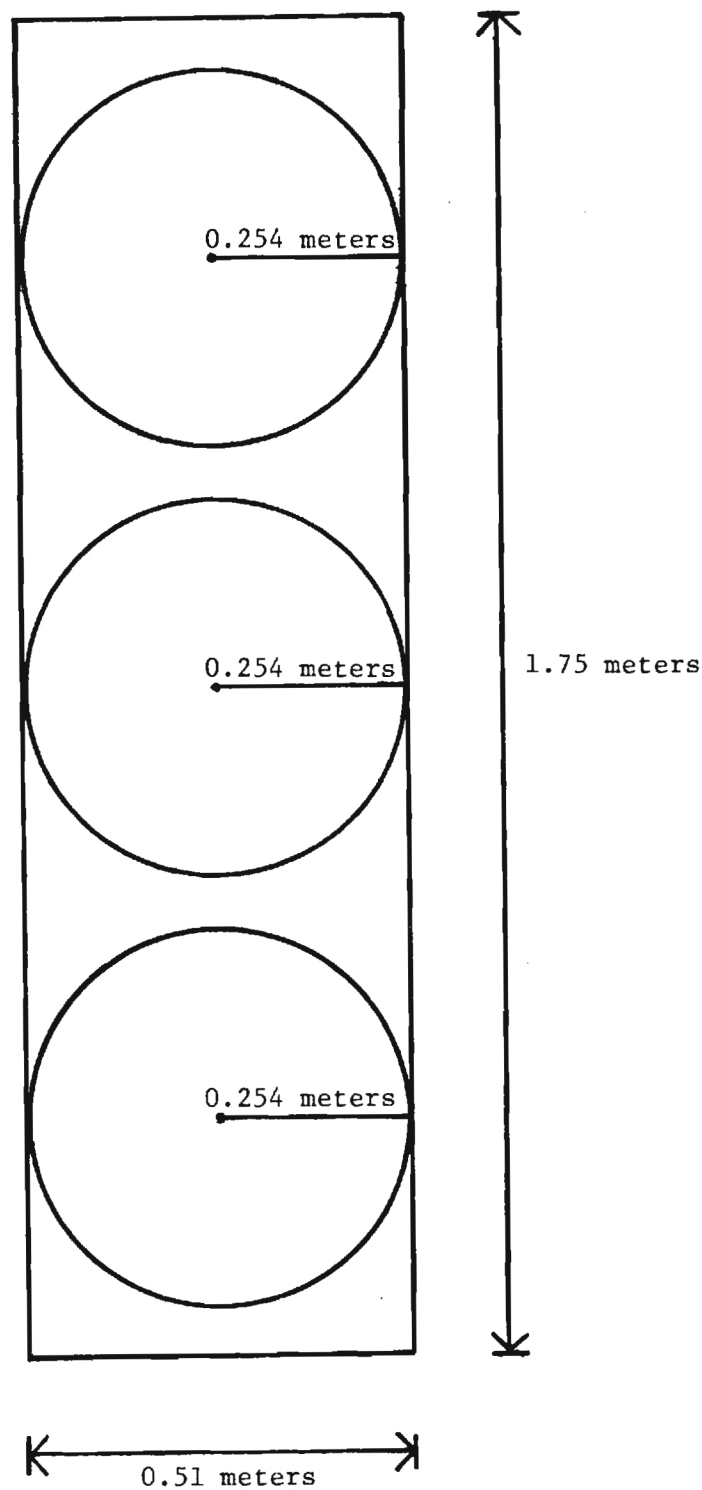


Figure 2. Model Cross Section of Man for Maximum Coupling to the Magnetic Field (which is normal to the paper). The circles represent induced currents.

TABLE 3
COMPARISON OF MODEL PREDICTIONS AND LITERATURE VALUES
FOR A PLANE WAVE WITH A 1 mW/cm^2 INCIDENT FIELD

FREQ.	Predicted Values			$\text{SAR}_{\text{LITERATURE}}$
	(W/kg) SAR_{E}	(W/kg) SAR_{H}	(W/kg) $\text{SAR}_{\text{TOTAL}}$	
10 kHz	4.75×10^{-9}	2.85×10^{-10}	5.03×10^{-9}	5×10^{-9}
100 kHz	3.09×10^{-7}	4.39×10^{-8}	3.53×10^{-7}	3×10^{-7}
1 MHz	2.77×10^{-5}	4.89×10^{-6}	3.26×10^{-5}	2.7×10^{-5}
3 MHz	2.39×10^{-4}	4.60×10^{-5}	2.43×10^{-4}	2×10^{-4}

Using conductivity values listed in Table 1, the model developed in this report predicts at 10 kHz:

$$\text{SAR} = 1.26 \times 10^{-12} E^2 + 1.08 \times 10^{-8} H^2 .$$

Again, the agreement is seen to be reasonable. For these reasons, the model was considered to be adequate for the purpose of analyzing hazards.

V. ANALYSIS OF HAZARDS

The simplified model discussed previously was next used to analyze potential hazards due to whole body SAR, localized SAR, body current, and localized current density. Shock and burn hazards were evaluated based on the model predictions and on literature values that define hazard threshold levels. These evaluations are discussed in this section of the report.

A. Analysis of 100 mW/cm² Standard

If existing standards [1] were extended into the 10 kHz to 3 MHz frequency range, then a power density of 100 mW/cm² might be considered a reasonable value for a safe exposure level. For this reason, the safety of exposure to a 100 mW/cm² plane wave was considered. In Table 4, the SAR from the electric and magnetic fields and the total SAR are tabulated as a function of frequency. Using 0.4 W/kg as the whole body SAR hazard threshold [1], it is clear that no hazards exist for this power density and frequency range if only whole body SAR is considered. This result was anticipated from the data previously mentioned in Table 2.

Having established that the whole body SAR values are acceptable for a 100 mW/cm² power density, it becomes necessary to examine the potential hazards associated with the induced body currents. In Table 5, the current densities and total body currents are listed for exposure to a 100 mW/cm² power density plane wave as a function of frequency. One should recall that the currents induced by the electric field flow along the long axis of the body, while the currents induced by magnetic field flow in loops. Also, note that the currents induced by the electric and magnetic fields will not be in phase. However, for simplicity to obtain the total body current, the current induced by the electric field was added to the current induced by the magnetic field; thus, a worst case analysis is obtained in a straightforward manner. The total body current was obtained by multiplying the current density by the cross sectional area of the body. The cross sectional area of the body was taken as 0.04 m² [3].

In Table 5, it can be seen that no values of current density for the indicated frequencies approach 1,000 A/m², which was the value Becker [14] found to be a burn producing level. Some of the values in the table exceed the value of 75 mA which can introduce ventricular fibrillation at a frequency of 60 Hz [7,8]. However, since no reports of induced ventricular fibrillation in the frequency range of interest could be found, these levels were not considered to be unacceptable though they should be regarded with some degree of caution. The hazard level of 200 mA [1] for body-

TABLE 4
SAR VALUES FOR A 100 mW/cm² EXPOSURE FIELD

FREQ.	(W/kg) SAR _E	(W/kg) SAR _H	(W/kg) SAR _{TOTAL}
10 kHz	4.75×10^{-7}	2.85×10^{-8}	5.03×10^{-7}
100 kHz	3.09×10^{-5}	4.39×10^{-6}	3.53×10^{-5}
1 MHz	2.77×10^{-3}	4.89×10^{-4}	3.26×10^{-3}
3 MHz	2.39×10^{-2}	4.60×10^{-3}	2.43×10^{-2}

TABLE 5
BODY CURRENT VALUES FOR A 100 mW/cm² EXPLOSURE FIELD

FREQ.	(A/m ²) J _E	(A/m ²) J _H	(A/m ²) J _{TOTAL}	(mA) TOTAL BODY CURRENT
10 kHz	1.43 x 10 ⁻²	3.50 x 10 ⁻³	1.78 x 10 ⁻²	0.712
100 kHz	1.43 x 10 ⁻¹	5.37 x 10 ⁻²	1.97 x 10 ⁻¹	7.88
1 MHz	1.43	5.99 x 10 ⁻¹	2.03	81.20
3 MHz	4.28	1.88	6.16	<u>246.40</u>

current induced shocks and burns was used to evaluate the danger level. At 3 MHz for a 100 mW/cm^2 incident power density and for plane wave exposure, the total body current just exceeds the hazard threshold (this value is underlined in the table).

Localized currents and SAR values could also be sources of potential hazards. To evaluate these potential hazards, it was assumed that the total body current flows through the given appendage for a "worst case" analysis. In those cases where a body part is in contact with a metal object which is intercepting radiofrequency radiation, this assumption is justified. The following cross sectional area values were used: man: 0.04 m^2 , finger: 10^{-4} m^2 , neck: 0.014 m^2 , wrist: 0.0024 m^2 , and ankle: 0.005 m^2 . Localized SAR values, SAR_L , were calculated from the localized current density, J_L , as follows:

$$\text{SAR}_L = \frac{J_L^2}{2\sigma\rho} \cdot$$

Using the methods discussed above, localized SAR values and current densities were calculated for a 100 mW/cm^2 power density, plane wave exposure. The results are shown in Table 6. Local SAR values exceeding 0.4 W/kg are underlined. The table shows that the local SAR of a finger in contact with a metal object (in this case the height of a man) will be dangerously high over most of the frequency range (heavy gloves would remedy this problem). Large local SAR values were also found in the wrist at 1 and 3 MHz and in the neck and ankle at 3 MHz. The case where the current density exceeded $1,000 \text{ amp/m}^2$ is also underlined (3 MHz in the finger).

Based on the results shown, a safety standard of 100 mW/cm^2 for the frequency range of 10 kHz to 3 MHz is not adequate. Whole body SAR is acceptable, but at the higher frequencies, total body current and localized SAR values in the wrist and ankle may prove to be too high. High localized values of SAR were calculated for a finger in contact with a metal object the height of a man. However, this problem could be resolved with thick insulating material and/or with current limiting devices. It should be emphasized that the calculations used here are approximate and are based on many simplifying assumptions. Experimental work should be done to determine whether a hazard does indeed exist.

B. Analysis of 1000 V/m Standard

For completeness, a standard which would permit plane wave exposures to fields with an electric field strength of $1,000 \text{ V/m}$ (a power density of 265 mw/cm^2) was

TABLE 6

LOCALIZED SAR AND CURRENT DENSITIES IN BODY PARTS (ASSUMING ALL BODY
CURRENT FLOWS THROUGH THE BODY PART) FOR 100 mW/cm^2 EXPOSURE

FREQ.	(A/m^2) J_{FINGER}	(W/kg) $\text{SAR}_{\text{FINGER}}$	(A/m^2) J_{NECK}	(W/kg) SAR_{NECK}	(A/m^2) J_{ANKLE}	(W/kg) $\text{SAR}_{\text{ANKLE}}$	(A/m^2) J_{WRIST}	(W/kg) $\text{SAR}_{\text{WRIST}}$
10 kHz	7.12	0.12	5.09×10^{-2}	6×10^{-6}	0.142	4.7×10^{-5}	0.300	2.1×10^{-4}
100 kHz	78.80	<u>9.44</u>	5.63×10^{-1}	4.82×10^{-4}	1.58	3.79×10^{-3}	3.28	1.64×10^{-2}
1 MHz	82.00	<u>898.3</u>	5.80	4.58×10^{-3}	16.24	0.359	33.83	<u>1.56</u>
3 MHz	<u>2464.00</u>	<u>7926</u>	17.60	<u>0.404</u>	49.28	<u>3.17</u>	102.67	<u>13.76</u>

considered. Calculations were made in a manner analogous to those described previously. The results of this work are presented in Table 7. The whole body SAR is well within acceptable levels as are the body current densities. The total body current, however, exceeds the 200 mA level by a factor of two at 3 MHz.

Localized values of the SAR and current density were also calculated. These values are listed in Table 8. Hazardous current densities were found for the case of a finger in contact with a metallic object the height of a man. This situation could be prevented with thick insulation and/or current limiting (or shunting) devices. High localized SAR values were found at 1 and 3 MHz for both the ankle and the wrist.

As a result of the data presented here, it appears that 1,000 V/m is too high a value for the electric field for safe exposure in the 10 kHz to 3 MHz frequency range. The local SAR values exceeded accepted safe levels by a considerable amount. Again, it should be emphasized that these calculations are approximate and should be used to indicate areas that need to receive closer scrutiny. Especially in those cases where the values predicted are very near threshold values that are reported to be hazardous, the predictions should be regarded cautiously. Numerous simplifying assumptions and "worst case" analyses were involved in arriving at the tabulated values.

C. Analysis of Body in Contact with Metal Objects

To a first approximation, a body in contact with a metal object may be treated as a body in contact with a voltage source. For ease of calculation and in order to obtain a worst case analysis, the impedance of the metal object/antenna will be taken as zero and the induced voltage may be taken as the height of the object times the electric field strength. The convenience of this approach is that the values calculated for dosimetry and currents given previously may be readily converted to values for a person in contact with an object. The current density and total body current values due to the electric field are multiplied by the ratio of the height of the metal object to the height of a man (1.75 m). The SAR_E values must be multiplied by the square of this ratio. The quantities affected by the magnetic field are not affected. Thus, a person in contact with a 30-meter tower exposed to a 100 mW/cm^2 plane electromagnetic wave will experience electric field current densities 17.1 times those values previously tabulated and SAR_E values 294 times as great.

In Table 9 and Table 10, body current densities, total body currents, whole body SAR values, localized SAR values, and localized current densities are tabulated for a man in contact with a 30-meter tower exposed to a plane wave with a 100 mW/cm^2 power density. Hazardous values of total body current, whole body SAR, localized

TABLE 7
VALUES OF SAR AND BODY CURRENTS FOR PLANE WAVE EXPOSURE
WITH ELECTRIC FIELD STRENGTH OF 1000 V/m

FREQ.	(W/kg) SAR _E	(W/kg) SAR _H	(W/kg) SAR _{TOTAL}	(A/m ²) J _E	(A/m ²) J _H	(A/m ²) J _{TOTAL}	TOTAL BODY CURRENT (mA)
10 kHz	1.26×10^{-6}	7.57×10^{-8}	1.34×10^{-6}	0.0232	5.69×10^{-3}	0.0289	1.16
1000 kHz	8.19×10^{-5}	1.16×10^{-5}	9.35×10^{-5}	0.232	8.75×10^{-2}	0.320	12.80
1 MHz	7.34×10^{-3}	1.30×10^{-3}	8.64×10^{-3}	2.32	0.976	3.30	132
3 MHz	6.33×10^{-2}	1.22×10^{-2}	7.55×10^{-2}	6.96	3.057	10.02	<u>401</u>

TABLE 8

VALUES OF CURRENT DENSITY AND LOCALIZED SAR FOR VARIOUS BODY PARTS FOR
PLANE WAVE EXPOSURE WITH AN ELECTRIC FIELD STRENGTH OF 1000 V/m

FREQ.	(A/m ²) J_{FINGER}	(W/kg) $\text{SAR}_{\text{FINGER}}$	(A/m ²) J_{NECK}	(W/kg) SAR_{NECK}	(A/m ²) J_{ANKLE}	(W/kg) $\text{SAR}_{\text{ANKLE}}$	(A/m ²) J_{WRIST}	(W/kg) $\text{SAR}_{\text{WRIST}}$
10 kHz	11.56	0.312	0.0826	1.59×10^{-5}	0.231	1.06×10^{-4}	0.482	5.43×10^{-4}
100 kHz	128.00	<u>24.90</u>	0.914	1.27×10^{-3}	2.56	9.96×10^{-3}	5.33	4.32×10^{-2}
1 MHz	<u>132.00</u>	<u>2374</u>	9.43	0.121	26.4	<u>0.950</u>	55.00	<u>4.12</u>
3 MHz	<u>4008.00</u>	<u>20971</u>	28.63	<u>1.07</u>	80.16	<u>8.39</u>	167.00	<u>36.41</u>

TABLE 9
BODY CURRENT VALUES IN A 100 mW/cm^2 EXPOSURE FIELD
WITH THE BODY IN CONTACT WITH A 30-METER TOWER

FREQ.	(A/m^2) J_E	(A/m^2) J_H	(A/m^2) J_{TOTAL}	TOTAL BODY CURRENT (mA)	(W/kg) SAR_E	(W/kg) SAR_H	(W/kg) $\text{SAR}_{\text{TOTAL}}$
10 kHz	0.245	3.50×10^{-3}	0.249	9.94	1.40×10^{-4}	2.85×10^{-8}	1.40×10^{-4}
100 kHz	2.45	5.37×10^{-2}	2.50	100.15	9.08×10^{-3}	4.39×10^{-6}	9.08×10^{-3}
1 MHz	24.50	5.99×10^{-1}	25.10	<u>1004.00</u>	<u>0.814</u>	4.89×10^{-4}	<u>0.814</u>
3 MHz	73.37	1.88	75.25	<u>3010.00</u>	<u>7.024</u>	4.60×10^{-3}	<u>7.029</u>

TABLE 10
LOCALIZED SAR AND CURRENT DENSITIES IN BODY PARTS (ASSUMING ALL
CURRENT FLOWS THROUGH THE BODY PART) IN A 100 mW/cm^2 FIELD
WITH THE BODY TOUCHING A 30-METER TOWER

FREQ.	(A/m^2) J_{FINGER}	(W/kg) $\text{SAR}_{\text{FINGER}}$	(A/m^2) J_{NECK}	(W/kg) SAR_{NECK}	(A/m^2) J_{ANKLE}	(W/kg) $\text{SAR}_{\text{ANKLE}}$	(A/m^2) J_{WRIST}	(W/kg) $\text{SAR}_{\text{WRIST}}$
10 kHz	99.60	<u>23.18</u>	0.711	1.18×10^{-3}	1.99	9.25×10^{-3}	4.15	0.040
100 kHz	<u>1000.0</u>	<u>1520</u>	7.14	7.75×10^{-2}	20.00	<u>0.608</u>	41.67	<u>2.64</u>
1 MHz	<u>10,040</u>	<u>137,332</u>	71.71	<u>7.01</u>	200.80	<u>54.93</u>	418.33	<u>238.42</u>
3 MHz	<u>30,100</u>	<u>1.18×10^6</u>	215.00	<u>60.35</u>	602.00	<u>473.11</u>	<u>1254.17</u>	<u>2053.45</u>

SAR, and localized current densities are evident over much of the frequency range. Some of the difficulty could be prevented with adequate insulation, current limiting contrivances, and/or current shunting devices.

The values listed in Tables 9 and 10 are approximate and are intended to establish an upper bound for the induced current and SAR. The method employed permits potential hazards to be calculated easily. It was for this reason that this method was employed.

VI. PROPOSED STANDARD

The objectives of this study are primarily to tentatively propose a safe exposure level, based upon our current knowledge, and to identify those areas where additional work should be done. In this section, the implications of the data presented are examined, and a safety standard based upon these data is discussed.

The results of this study have shown that if whole body SAR is used as the sole basis for formulating a safety standard, then relatively high power densities would be acceptable. However, total body currents, total body current densities, localized SAR values, and localized current densities may reach unacceptable levels, even for plane wave exposures at power densities of 100 mW/cm^2 . The excessive localized SAR values obtained for contact with metal objects (finger data and contact with a 30-meter tower) indicate that some provision should be made in the standard for methods of minimizing contact hazards. This may be accomplished by determining the quantity and type of insulation that should be used to prevent excessive currents (the model discussed above with the insulation modeled as a capacitor is a reasonable approach for predicting the currents). Grounding straps or other means of shunting or limiting the current could also be specified. A future study is needed to identify appropriate specifications for the insulating materials and other current shunting and limiting techniques.

Using total body current as the only parameter upon which a standard would be based, a safe exposure level appears to be 65 mW/cm^2 . However, localized SAR data indicate that this level would still permit high localized SAR values to occur. If localized SAR values as high as 8 W/kg [1] were considered acceptable, then based on ankle data, the safety standard could be set at 252 mW/cm^2 . Finally, if no localized values of SAR higher than 0.4 W/kg were to be tolerated, then the standard would be set at 14 mW/cm^2 .

The preceeding discussion is based on localized SAR values in the ankle because they are more realistic than localized SAR values for the wrist. In both cases, it is assumed that the total body current flows through the subject body part, but this assumption is more likely to be true for the ankle than for the wrist.

In the discussion above, it is also assumed that the standard is constant over the entire frequency range, which is an extremely conservative approach in which the acceptable power level for 3 MHz exposure dictates the acceptable power level at all frequencies. However, it is evident from the mathematical models used that the acceptable power level goes up inversely with the square of the frequency. Thus, if 14

mW/cm^2 is safe at 3 MHz, then $1.26 \times 10^6 \text{ mW/cm}^2$ would be tolerated at 10 kHz. The latter value is in the range where high field gradients could cause bioeffects. To avoid this potential problem, it is suggested that the electric field intensity should not exceed a value of approximately 1,000 V/m.

A tentative safety standard can be derived from the discussions in this section depending upon the maximum allowable value of the SAR, localized SAR, electric field intensity, and current density. A conservative standard based upon a maximum localized value of SAR of 0.4 W/kg and a maximum electric field intensity of 1,000 V/m is 14 mW/cm^2 at 3 MHz rising inversely with the square of the frequency to 265 mW/cm^2 at 690 kHz then remaining at the constant value of 265 mW/cm^2 from 690 kHz to 10 kHz. Of course provisions for protective equipment should be considered in the vicinity of towers.

The recommendations made above are tentative, because they are based on an approximate model and on parameter levels which need to be investigated further for this frequency range. Therefore, a great deal of work needs to be performed to resolve various problems; consequently, the standards proposed here may prove to be far too conservative.

VII. PROBLEMS AND AREAS FOR FUTURE RESEARCH

Numerous problems, which span many areas, should be resolved before a safety standard in the 10 kHz to 3 MHz frequency range can be proposed with total confidence. Rigorous theoretical work involving the accurate prediction of ankle and neck currents should prove useful. Experimental work must be initiated to determine localized SAR values and currents in the body parts. This work should involve living volunteers as well as phantoms and perhaps cadavers. Without such studies, the hazard levels will always remain a matter of conjecture.

In addition to accurate measurements of the current, current density, and localized SAR levels, it is necessary to accurately determine what levels of these parameters are hazardous in the 10 kHz to 3 MHz frequency range. The hazards which should be considered include shocks, burns, and current levels that incapacitate vital body functions (such as current levels necessary for ventricular fibrillation).

The experiments that should be conducted should include efforts to quantify hazards not only in terms of total body current, but also in terms of current density. It is conceivable that a safe level of whole body current flowing through a narrow body region may cause burns or other hazards. Similarly, tolerable localized SAR values will very likely be a function of the volume of the localized area. Studies to determine the level of localized SAR as a function of the heated volume in the presence of blood flow and tissues or phantom materials, whose electrical and thermal properties closely resemble living tissue, are essential.

Even with very conservative standards applied to current densities and localized SAR values, as indicated previously in this report, very large values of electric field strength based on these parameters would be considered acceptable at the lower frequencies. Some research has been reported that involves investigating the effects of very large electric fields and electric field gradients upon biological systems and models of systems [15-23, 27]. Eventually, some rationale will be required for determining what the maximum permissible electric field strength will be and whether it is necessary to establish a maximum electric field gradient as well. Research in these areas should be performed both at the molecular (or at least the cellular) level as well as at the whole organism level. The results of such research should prove to be valuable both in setting a prudent safety standard and to other areas of biotechnology.